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EFFECT OF WATER INJECTION ON NITRIC OXIDE EMISSIONS OF A GAS TURBINE COMBUSTOR BURNING NATURAL GAS FUEL

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16. Abstract
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SUMMARY

The effect of direct water injection on the exhaust gas emissions of a turbojet combustor burning natural gas fuel was investigated. The results are compared with the results from similar tests using ASTM Jet-A fuel.

The combustor was operated over a range of inlet-air temperatures from 589 to 894 K (600° to 1150° F). Water was injected into the combustor primary zone. Increasing water injection decreased the emissions of oxides of nitrogen (NO_x) and increased the emissions of carbon monoxide (CO) and unburned hydrocarbons (H/C). The greatest percentage decrease in NO_x was at the lowest inlet-air temperature tested, 589 K (600° F). The effect of increased inlet-air temperature was to decrease the effect of the water injection.

The reduction in NO_x due to water injection is almost identical to the results obtained with Jet-A fuel. The emissions of H/C, however, were much higher with natural gas fuel than with Jet-A and composed the larger percentage of combustion inefficiency at the high water-fuel ratios.

The principal effect of water injection on NO_x was to decrease the nitrix oxide (NO) emission index while the nitrogen dioxide (NO_2) emission index remained fairly constant. With Jet-A fuel both the NO and NO_2 emission levels were decreased.

INTRODUCTION

The effect of direct water injection on the exhaust gas emissions of a 107-centimeter (42-in.) diameter annular turbojet combustor burning natural gas fuel was investigated. The measured pollutants included oxides of nitrogen (NO_x) unburned hydrocarbons (H/C), and carbon monoxide (CO).

The rate of formation of nitric oxide (NO) in combustion flames is strongly depend-

ent on the flame temperature. Significant decreases in nitric oxide concentrations have been found by injecting water into the combustion zone. Hilt and Johnson (ref. 1) used up to 1 percent water (based on air flow) injection to lower the nitric oxide emissions of gas turbines used for stationary power. No significant increase in unburned hydrocarbons and carbon monoxide was noted in their tests.

The use of water injection for abatement of nitric oxide emissions is important in that it lowers the flame temperature by evaporation and by the water vapor's higher specific heat. The amount of water vapor in the ambient air (humidity) has already been shown to have a significant effect on the formation of oxides of nitrogen (refs. 2 to 4), attributed to the specific heat difference alone.

Excess water injection may be responsible for a decrease in combustion efficiency which may be measured as an increase in the emissions of unburned hydrocarbons and carbon monoxide. Previous tests with ASTM Jet-A liquid fuel (ref. 5) showed a decrease in the combustion efficiency at water-fuel ratios greater than one-half. Some methods of water injection may appear to be more successful in maximizing the reduction in nitric oxide emissions while minimizing the increases in the other pollutants (ref. 6).

The tests reported herein were performed to determine whether the fuel properties of natural gas significantly affected the reduction of NO_x and the increase in CO and H/C due to water injection. Previous work with natural gas (~94 percent methane) has shown that a combustor's efficiency decreased when operated with vitiated inlet air, especially at severe operating conditions (ref. 7). The decrease in efficiency in those tests was primarily attributed to the reduction in oxygen concentration. It should also be pointed out that the narrow stability limits and high thermal stability of methane make the combustion of natural gas particularly sensitive to changes in oxygen concentration and temperature. The combustor used in these tests is the same combustor used in the tests with liquid fuel (ref. 5), with modified fuel nozzles. The water injection method is also the same.

The combustor was designed for a turbofan engine having supersonic cruise capability. Tests were conducted over a range of inlet-air temperatures from 589 to 894 K (600° to 1150° F) at six atmospheres pressure and at reference Mach numbers from 0.064 to 0.078. These inlet-air temperatures and reference Mach numbers simulate sea-level takeoff conditions for gas turbine engines over a range of engine pressure ratios.

Water at ambient temperature was injected into the combustor primary zone at water-fuel ratios up to two. The combustor was operated at a constant fuel-air ratio while varying the water injection rate.

Exhaust gas emissions data were taken at all test conditions. No smoke data were taken since previous experience with burning natural gas in this combustor produced no significant smoke.

FACILITY

Testing was conducted in a close-duct test facility at the Lewis Research Center. A schematic of this facility is shown in figure 1. A detailed description of the facility and instrumentation are contained in reference 8. All fluid flow rates and pressures were controlled remotely.

TEST COMBUSTOR

The combustor tested was designed using the ram-induction approach and is described in reference 9. A cross section of the combustor is shown in figure 2. The compressor discharge air is diffused less than it is in conventional combustors. The relatively high-velocity air is captured by scoops in the combustor liner and turned into the combustion and mixing zones. Vanes are used in the scoops to reduce pressure loss caused by the high-velocity turns. The high-velocity and the steep angle of the entering air jets promote rapid mixing of both the fuel and air in the combustion zone and of the burned gases and air in the dilution zone. The potential result of rapid mixing is a shorter combustor or, alternatively, a better exit temperature profile in the same length. The combustor's outside diameter is almost 1.07 meters (42 in.), and the length from compressor exit to turbine inlet is approximately 0.76 meter (30 in.). A snout on the combustor divides the diffuser into three concentric annular passages. The central passage conducts air to the combustor headplates, and the inner and outer passages supply air to the combustor liners. There are five rows of scoops on each of the inner and outer liners to turn the air into the combustion and dilution zones. Photographs of the snout and the combustor liners are shown in figure 3. Figure 3(a) is a view looking upstream into the combustor liner. The scoops in the inner and outer liner and the openings in the headplate for the fuel nozzles and swirlers can be seen. Figure 3(b) is a view of the snout and the upstream end of the combustor liner. The V-shaped cutouts in the snout fit around struts in the diffuser. The circular holes throught the snout walls are for the fuel nozzle struts. Figure 3(c) gives a closer view of the liner and headplate showing liquid fuel nozzles and swirlers in place. There are 24 fuel nozzles in the combustor. The fuel nozzles were modified for use with natural gas. Figure 4 shows a gas fuel nozzle and its installation. The nozzle has six 0.476-centimeter (0.188-in.) diameter holes at a 13.5° angle from the nozzle centerline. Fuel flow was restricted by the small supply hole through the fuel strut, which was originally designed for liquid fuel.

WATER INJECTION

Water was injected into the combustor at 24 locations upstream of the fuel spray nozzles. Figure 5 shows an exterior view of the combustor housing and shows the location of both water and fuel injection nozzles. A photograph of a water spray nozzle is shown in figure 6. The nozzle produces a flat fan spray into the center fuel-nozzle-snout volume. All the water passes into the combustion zone through the air swirlers and slots around the combustion headplate. Some of the water vaporizes due to atomization, the high inlet-air temperature, and impingement on the back of the combustor headplate. No attempt was made to calculate the percentage of water that was vaporized before entering the combustor.

All the water used in these tests was demineralized by a chemical process. This was necessary to prevent a gradual buildup of scale on the combustor which could potentially seal many small air entry holes and slots.

TEST CONDITIONS

Tests were conducted at six atmospheres pressure and at a constant inlet airflow of about 50 kilograms per second (110 lb sec) over a range of inlet-air temperatures from 589 K (600° F) to 894 K (1150° F). The nominal test conditions are listed in table I. The fuel-air ratio was approximately constant at 0.0155 which was the maximum limit of the fuel supply system. Some additional data were taken at a lower fuel-air ratio of 0.0123 at the 755 K (900° F) inlet-air temperature condition.

INSTRUMENTATION

Exhaust Gas Temperatures

Combustor exhaust gas temperatures were measured at 3° increments around the circumference with three five-point aspirated thermocouples probes that traverse circumferentially in the exit plane. Five hundred eighty-five individual exit temperatures were used in each mass-weighted average exit temperature calculation. The exhaust gas temperature was used only as a check on combustion efficiency, which was primarily measured by gas sampling.

Exhaust Gas Sampling

Concentrations of nitric oxide, total oxides of nitrogen, carbon monoxide, unburned hydrocarbons, and carbon dioxide were obtained with an on-line system. The samples were drawn at the combustor exit from three circumferential locations, 120° apart, and at five radial positions, through water-cooled stainless-steel probes. The exit instrumentation plane is shown in figure 2. A photograph of the sample probe is pictured in figure 7.

Gas sample system. -The samples collected by the three sample probes were formed into one common sample line. Approximately 18 meters (60 ft) of 0.95 centimeter (3/8 in.) stainless-steel line was used to transport the sample to the analytical instruments. In order to prevent condensation of water and to minimize adsorption-desorption effects of hydrocarbon compounds, the line was electrically heated to 428 K (310° F). Sample line pressure was maintained at 6.9 newtons per square centimeter (10 psig) in order to supply sufficient pressure to operate the instruments. Sufficient sample is vented at the instruments to provide a line residence time of about two seconds.

The exhaust gas analysis system, shown in figure 8, is a packaged unit consisting of four commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration. In addition to visual readout, electrical inputs are provided to an IBM 360 computer for on-line analysis and evaluation of the data.

The hydrocarbon content of the exhaust gas is determined by a Beckman Instruments Model 402 Hydrocarbon Analyzer. This instrument is of the flame ionization detector type.

The concentration of the oxides of nitrogen is determined by a Thermo Electron Corporation Model 10A Chemiluminescent Analyzer. The instrument includes a thermal converter to reduce NO_2 to NO and was operated at 972 K (1290° F). Both carbon monoxide and carbon dioxide analyzers are of the nondispersive infrared (NDIR)-type (Beckman Instruments Model 315B). The CO analyzer has four ranges: 0 to 100 ppm, 0 to 1000 ppm, 0 to 1 percent, and 0 to 10 percent. This range of sensitivity is accomplished by using stacked cells of 0.64 centimeter (0.25 in.) and 34 centimeters (13.5 in.) length. The CO_2 analyzer has two ranges, 0 to 5 percent and 0 to 10 percent, with a sample cell length of 0.32 centimeter (0.125 in.).

Analytical procedure. -All analyzers were checked for zero and span before the test. Solenoid switching within the console allows rapid selection of zero, span, or sample modes. Therefore, it was possible to perform frequent checks to insure calibration accuracy without disrupting testing.

Where appropriate, the measured quantities were corrected for water vapor removed. The correction inluded inlet air humidity, water injected, and water vapor from combustion. The equations used were obtained from (ref. 10).

The emission levels of all the constituents were converted to an emission index (EI) parameter. The EI may be computed from the measured quantities as proposed in (ref. 10) or from the metered fuel-air ratio when this is accurately known. Using the latter scheme the EI for any constituent X is given by

$$EI_X = \frac{M_X}{M_E} \frac{(1+f)}{f} [X] \times 10^{-3}$$

where

EI_X emission index in grams of X per kg of fuel burned

M_X molecular weight of X

M_E average molecular weight of exhaust gas

f metered fuel-air ratio (g fuel/g inlet air plus water injected)

[X] measured concentration of X, ppm

Both precedures yield identical results when the sample validity is good.

RESULTS AND DISCUSSION

Exhaust Gas Pollutants

The effect of water injection on the exhaust gas emissions at all test conditions is shown in figure 9. The data are plotted on semilog coordinates because the NO_X emission index was found to decrease exponentially with water injection in an earlier reported work with Jet-A fuel (ref. 5).

The trends in the emission index data are the same for all test conditions. The effect of increasing water injection is to decrease the NO_X emission index and to increase the emission indices of carbon monoxide and unburned hydrocarbons. At the lowest inlet-air temperature tested, 589 K (600° F), the combustor blew out at a water-fuel mass ratio of approximately 1.3. The combustor blowout is consistent with the high amounts of CO and unburned hydrocarbons measured at a water-fuel ratio near 1.0.

At the higher inlet-air temperatures tested (figures 9 (b) through (d)), combustor blowout did not occur within the range of water-fuel mass ratios tested. CO and H/C emission indices decrease, as expected, with increasing inlet-air temperature. The

effect of increasing water injection is to produce large increases in CO and H/C emissions, indicating that the water injection is effecting the combustion process.

At a lower fuel-air ratio of 0.0123 (solid symbols is figure 9 (b)), the CO and H/C emission indices are greater than the values obtained with a fuel-air ratio of 0.0155. It is interesting to note, however, that the variation in fuel-air ratio did not significantly effect the NO_x emission index.

The decrease in NO_x emission index with increasing water injection in these tests is similar to the results obtained with liquid Jet-A fuel in previous work (ref. 5). Figure 10 shows the effect of water injection on the NO_x emission index when normalized to the emission index with zero water injection for each inlet-air temperature. The results obtained with liquid fuel (ref. 5) are shown as the shaded area. With both fuels, the effect of increasing inlet-air temperature was to decrease the effect of the water injected. Approximately a 50-percent reduction in NO_x was accomplished at a water fuel ratio of 0.55 for an inlet-air temperature of 589 K (600° F). The same reduction in NO_x at an inlet-air temperature of 894 K (1150° F) required a water-fuel ratio of approximately 0.70. This is probably due to preheating and prevaporizing of the water by the higher inlet-air temperature and hotter combustor hardware. Preheating and prevaporizing of the water lowers its effectiveness in cooling the primary zone flame temperature.

Oxides of nitrogen. -In the work of reference 5 with Jet-A fuel and in this work, the NO_x emission index appears to decrease almost exponentially with increasing water-fuel ratio The number of data points outside the shaded area in figure 10 at the higher water-fuel ratios suggest that possibly an additional factor be considered. From thermodynamic considerations, the heating value of the fuel should be taken into account in order to correlate different fuels and the flame temperature with water injection. The lower heating value of natural gas is approximately 5.00×10^{7} joules per kilogram (21 500 Btu/lb) compared with 4.33×10^{7} joules per kilogram (18 600 Btu/lb) for Jet-A fuel. The NO_x emission index for the same combustor and different fuels may be expected to correlate with flame temperature and the flame temperature to be a function of the water-fuel mass ratio adjusted for the difference in lower heating value between the fuels. The water-fuel mass ratio of natural gas may be adjusted to a Jet-A basis by the inverse ratio of the lower heating values:

$$\frac{W}{F_{ADj}} = \frac{W}{F} \frac{\text{LHV (Jet-A)}}{\text{LHV (natural gas)}} \quad F$$

where W/F is the water-fuel mass ratio of the data taken with natural gas and the LHV (fuel) are the lower heating values of the respective fuels.

Figure 11 shows the effect of water injection on NO_x emission index using the adjusted water-fuel ratios for the natural gas data. The decrease in NO_x emission index

with water injection for natural gas correlates almost exactly with the Jet-A data when the water-fuel ratio is adjusted by the differences in fuel lower heating value.

Inlet air humidity. -Inlet air humidity H was measured near the air orifice and was 0.0058±0.0016 gram water per gram dry air over the period that tests were conducted. The effect of inlet-air humidity is to decrease the NO_x emission index with increasing humidity that is, $NO_x = NO_{x_0} e^{-19H}$, where NO_{x_0} indicates that NO_x value at zero humidity (ref. 2). The NO_x emission index values shown in this report are the measured values. If the test were conducted at another significantly different value of inlet air humidity, the NO_x emission index values would be expected to be effected. However, the normalized relations shown in figures 10 and 11 would not be expected to change.

Combustion efficiency. -Combustion efficiency as determined by gas sampling is shown in figure 12 for the conditions tested. At water-fuel ratios less than 0.5, combustion efficiency is greater than 90 percent at all the test conditions. At higher water-fuel ratios, combustion efficiency decreases rapidly with increasing water-fuel ratio, especially at the lower inlet-air temperatures. These values of combustion efficiency are computed from CO and H/C emission indices (measures of inefficiency) shown in figure 9.

The combustion efficiency for this combustor with natural gas fuel at high water-fuel ratios is poorer than with Jet-A fuel (ref. 5). Figure 13 shows a comparison of the combustion efficiency of the two fuels with water injection at inlet-air temperatures of 589 and 894 K (600° and 1150° F), the low and high inlet-air temperature limits of the data taken. The water-fuel ratios are adjusted for the enthalpy differences of the fuels to a Jet-A basis. Combustion efficiency with water injection is notably better with Jet-A fuel. The difference in combustion efficiency between the two fuels at high water-fuel ratios is primarily due to the amount of unburned hydrocarbons. Figure 14 shows the emission indices of CO and H/C for natural gas and Jet-A at the two inlet-air temperatures. The CO emission index for natural gas is slightly higher than for Jet-A; but the CO values for both fuels are of the same order of magnitude. The H/C emissions, however, differ by almost two orders of magnitude for the two fuels. The larger amount of H/C present with natural gas is attributed to the fundamental stability of the methane molecule. (Other indicators of its molecular stability are methane's high heat capacity, high temperature before thermal decomposition, and narrow flammability limits.)

Data for inlet-air temperatures between 589 and 894 K (600° and 1150° F) shown in figures 13 and 14 fall between the limits shown for those temperatures.

Oxides of nitrogen and carbon monoxide. -Figure 15 shows the relation between NO_x and CO emissions with water injection. The figure illustrates the tradeoff between decreasing NO_x emissions with increasing CO emissions when water injection is used

with this combustor burning natural gas fuel. Also included on the figure are the bounds of data taken with Jet-A fuel from (ref. 5). Only the natural gas data taken at approximately 0.015 fuel-air ratio are included since it has already been shown in figure 9(b) that variations in fuel-air ratio affect the CO emission index but not the NO_x emission index at those conditions. It has also been shown in reference 5 that variations in inlet air humidity cause variations in NO_x emissions index without effecting the CO emission index. This is especially true with good efficiency or low CO emission index with Jet-A fuel.

Nitric oxide. -Nitric oxide (NO) made up approximately 90 percent of the NO_x emission index without water injection. This is the same percentage NO in NO_x found with Jet-A fuel in references 2 and 5. With increasing water injection, the percentage of NO in NO_x decreased as shown in figure 16.

The effect of water injection on NO_x was principally to decrease the NO emission index. The level of NO_2 emission index remained fairly constant as shown in figure 17. When similar tests were run with Jet-A fuel, both NO and NO_2 emission levels were decreased (ref. 5).

Sample Validity

A comparison of gas sample to metered fuel-air ratio for all the data is shown in figure 18 plotted against water-fuel ratio. Most of the data exhibit a scatter of ±2.5 percent about a mean value of 1.070. The fact that the mean value is 7 percent high is probably due to the location of the three gas sample probes.

SUMMARY OF RESULTS

The effect of direct water injection on the exhaust gas emissions of a turbojet combustor burning natural gas fuel was investigated. The following results were obtained:

1. Increasing water injection decreased the oxides of nitrogen (NO_x) emission index and increased the emissions of carbon monoxide and unburned hydrocarbons. The greatest percentage decrease in NO_x was at the lowest inlet-air temperature tested, 589 K (600° F). At this temperature, the NO_x was reduced at an almost constant exponential rate.

2. The effect of increasing inlet-air temperature was to decrease the effect of the water injection. At an inlet-air temperature of 589 K (600° F), a 50 percent reduction in NO_x was accomplished by a water-fuel ratio of approximately 0.55. At 894 K (1150° F), the same reduction in NO_x required a water-fuel ratio of approximately 0.70.

3. When the water-fuel mass ratio was adjusted for the difference in lower heating value between natural gas and Jet-A fuel, the reduction in NO_x due to water injection was almost identical to the results obtained with the same combustor and Jet-A fuel.

4. Combustor blowout occurred at an inlet-air temperature of 589 K (600^o F), pressure of six atmospheres, and water-fuel ratio of approximately 1.3 as a result of the water injection.

5. The emissions of unburned hydrocarbons were at least an order of magnitude higher with natural gas than with Jet-A fuel and composed the larger percentage of combustion inefficiency at the high water-fuel ratios.

6. The effect of water injection on NO_x was principally to decrease the nitric oxide (NO) emission index. The level of the nitrogen dioxide (NO_2) emission index remained fairly constant with water injection. When similar tests were run with Jet-A fuel, both the NO and NO_2 levels of emissions were decreased.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 16, 1973,
501-24.

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TABLE I. -COMBUSTOR NOMINAL TEST CONDITIONS

[Combustor pressure, 6 atmospheres; inlet-air flow, 49.89 kg/sec (110 lb/sec).]

Condition	Inlet-air temperature		Reference Mach number	Fuel-air ratio
	K	°F		
1	589	600	0.064	0.0158
2	755	900	.072	.0155
3	838	1050	.076	.0155
4	894	1150	.078	.0151

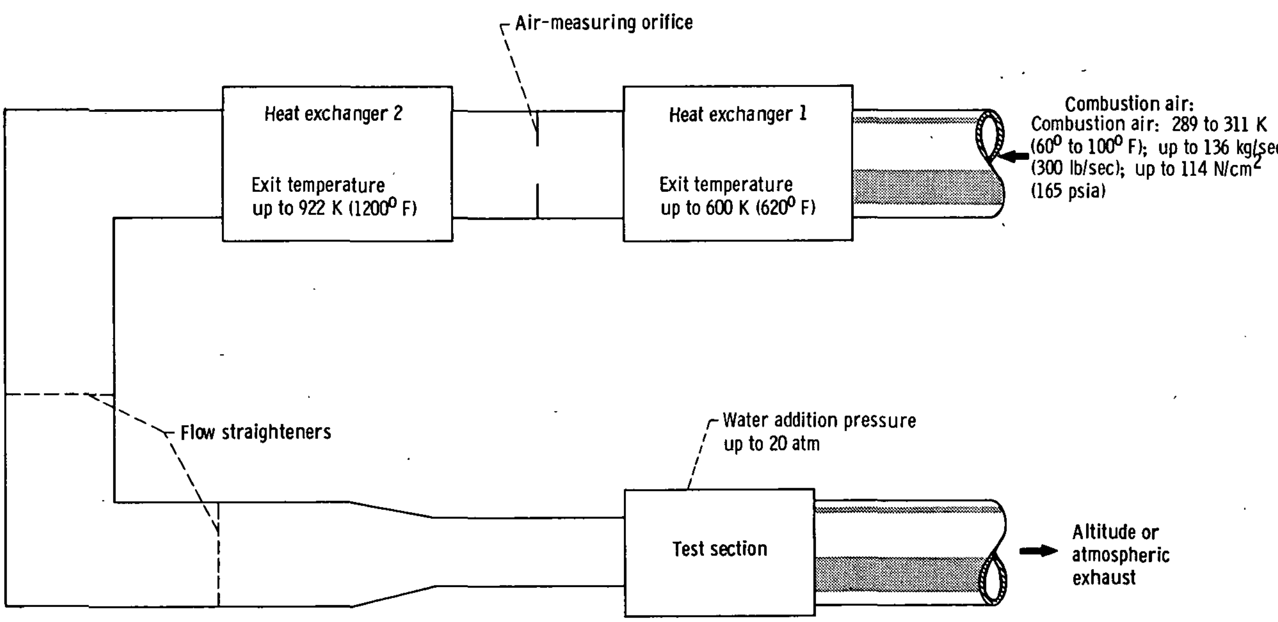


Figure 1. - Schematic of test facility.

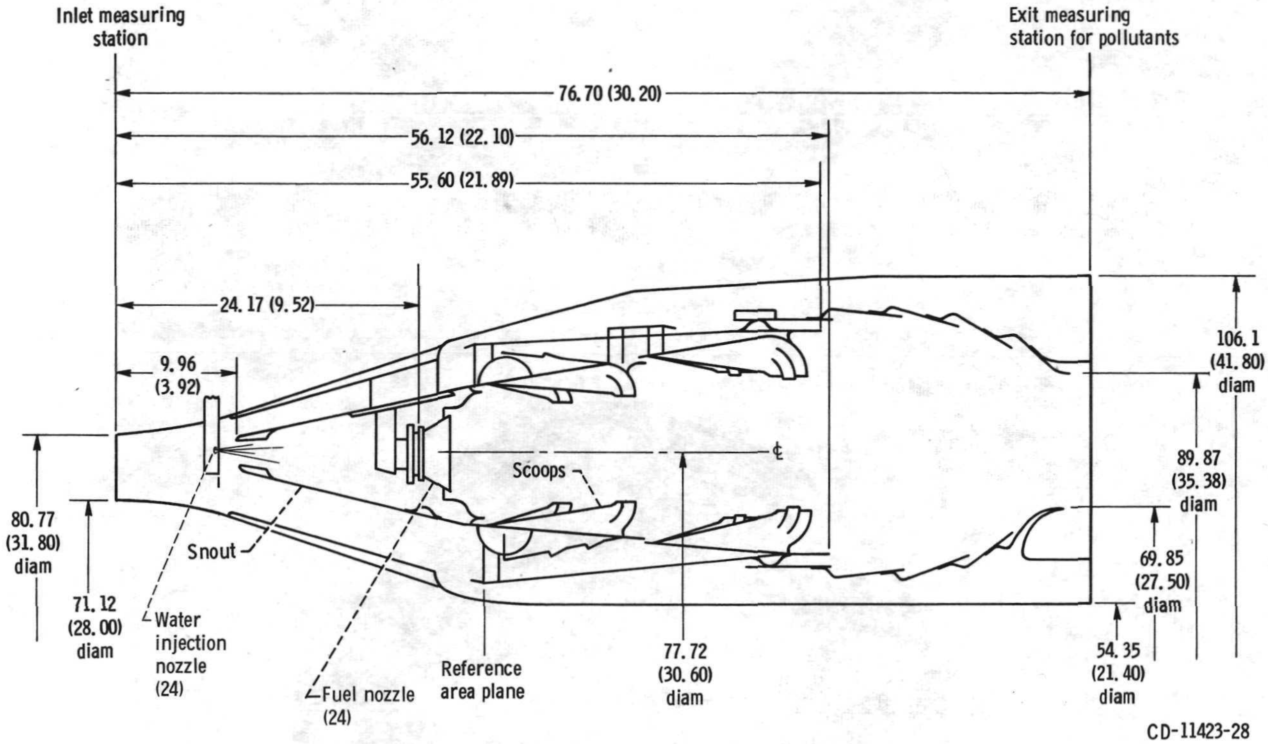
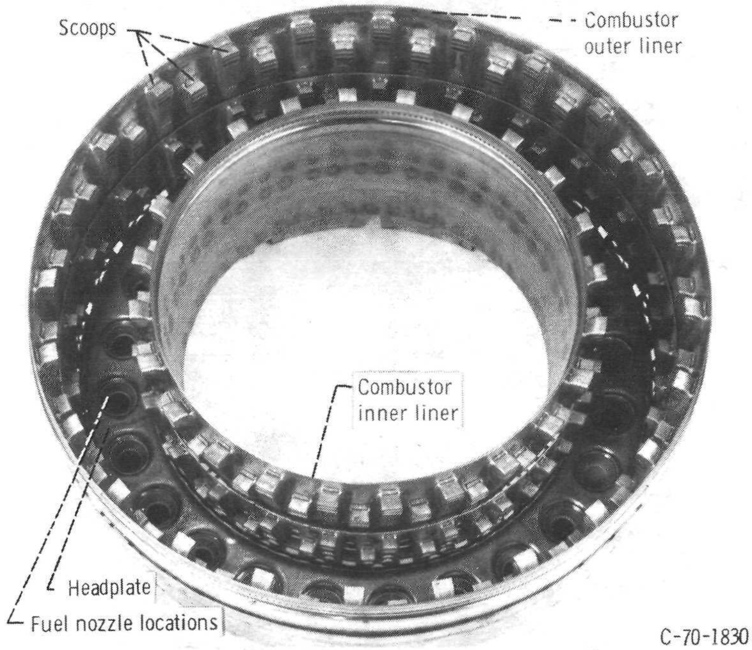
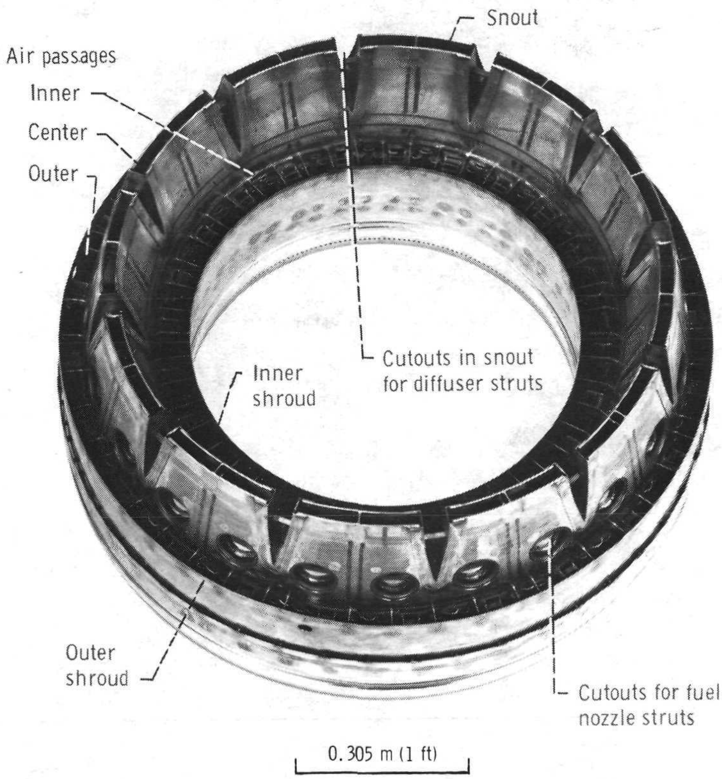


Figure 2. - Cross section of combustor. (Dimensions are in cm (in.).)

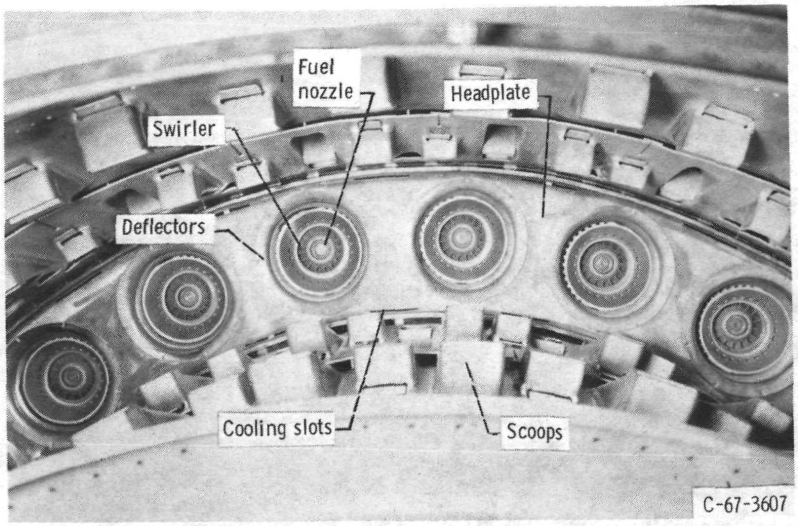


(a) View from downstream end.



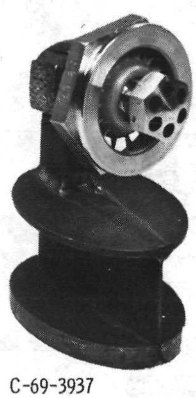
(b) View from upstream end.

Figure 3. - Annular ram-induction combustor.



(c) Closeup view from downstream end.

Figure 3. - Concluded.



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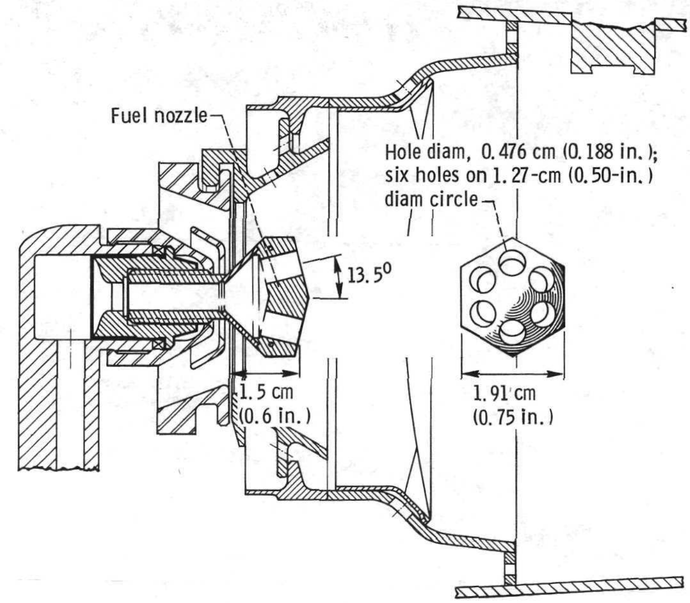

Figure 4. - Natural gas fuel nozzle.

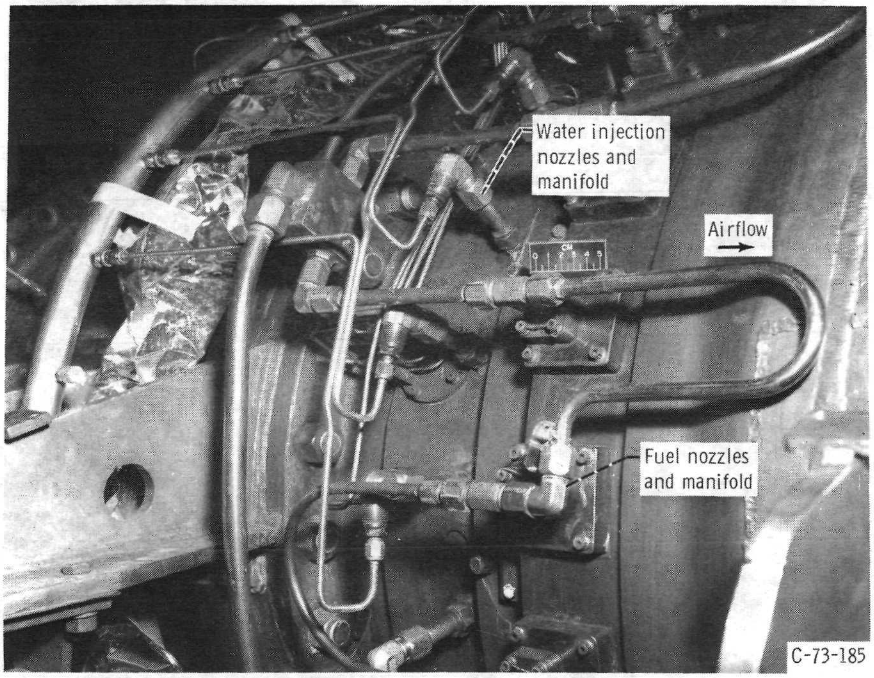

Figure 5. - Exterior of combustor housing showing location of fuel and water injection nozzles.

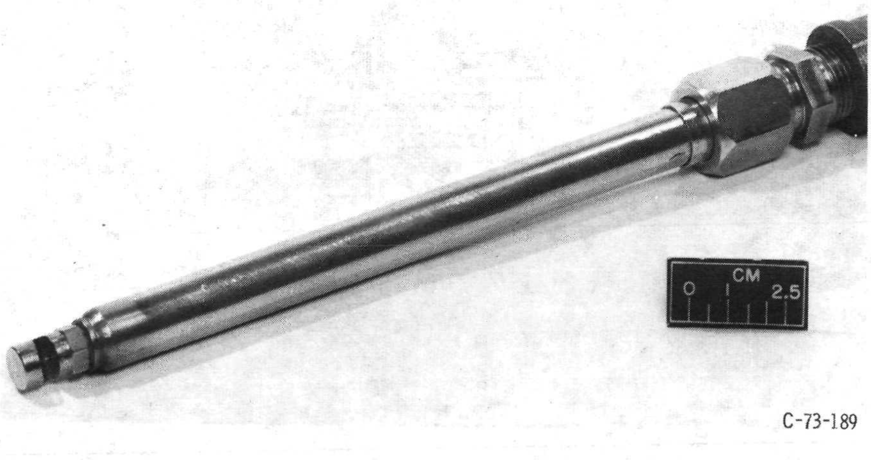

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Figure 6. - Water injection nozzle.

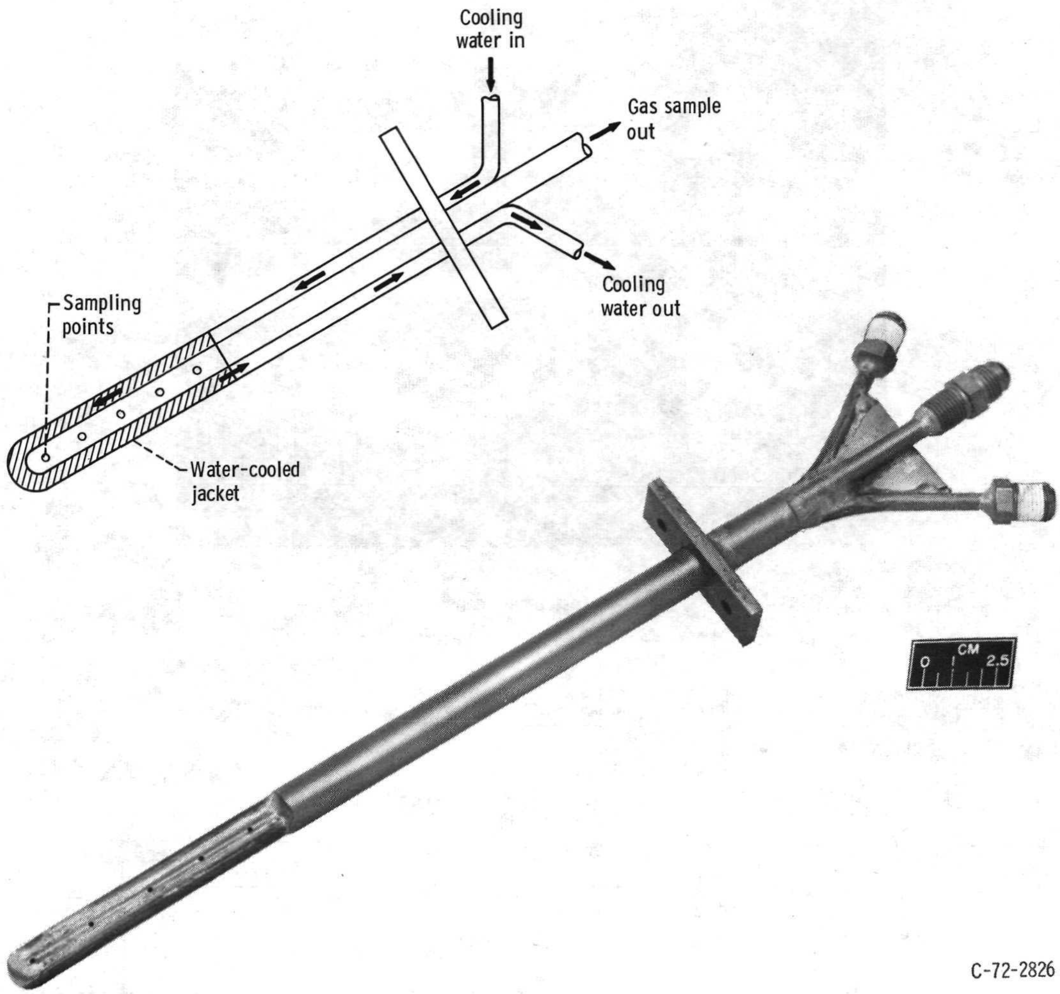
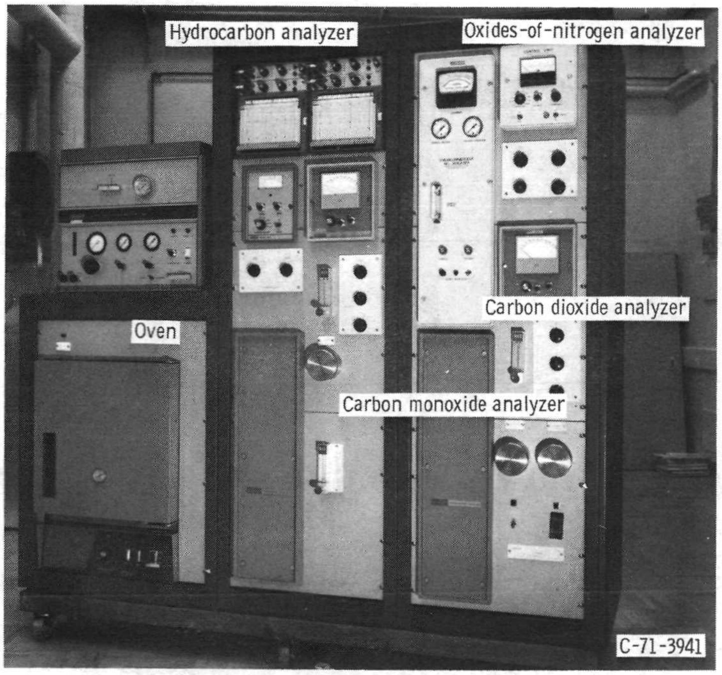
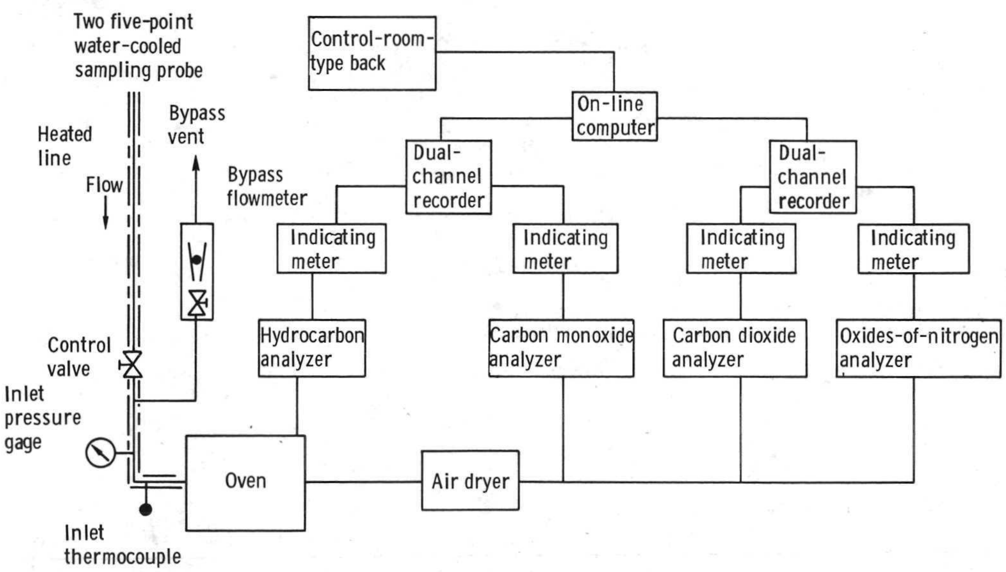


Figure 7. - Gas sampling probe.

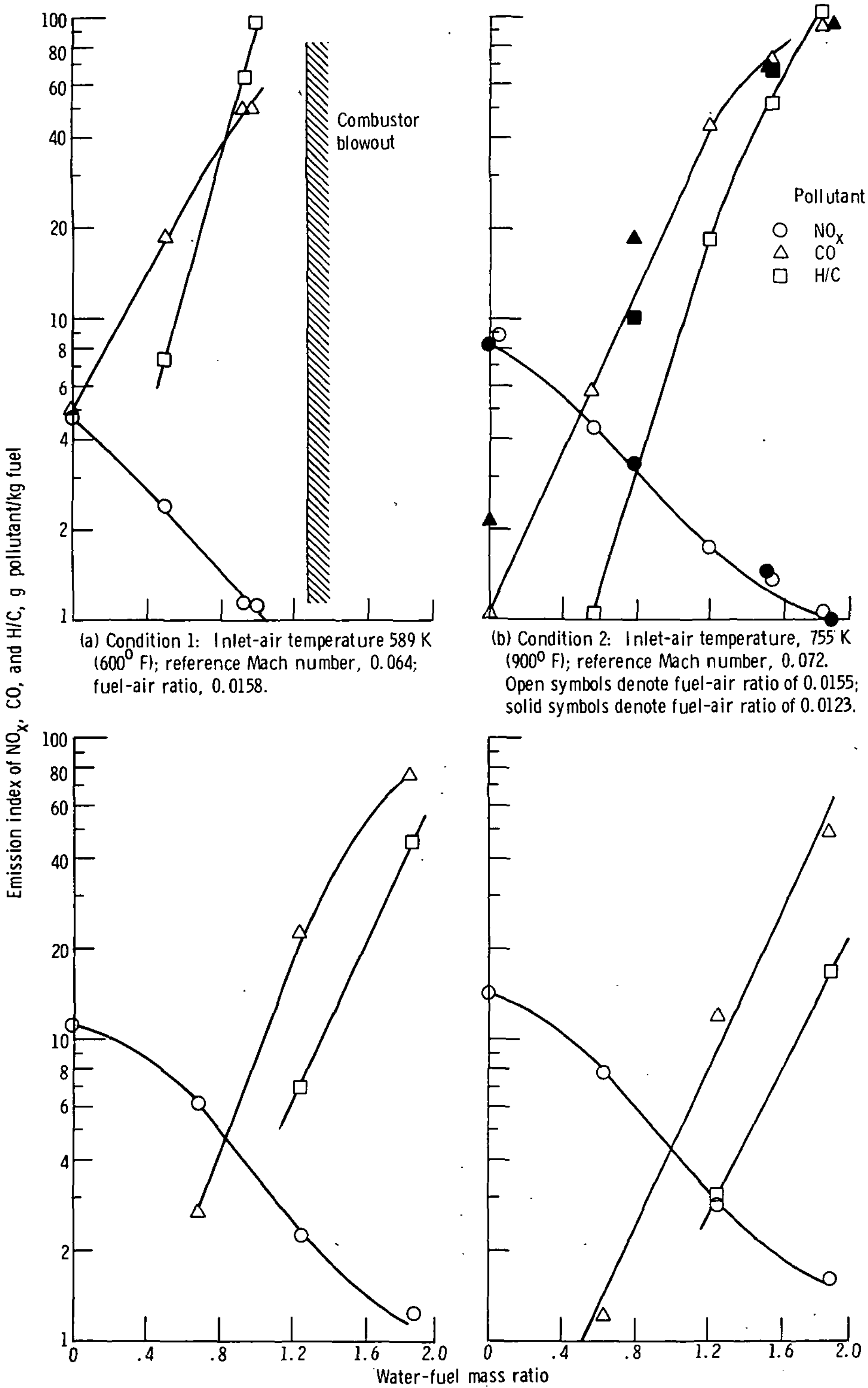


(a) Instrument console.



(b) Schematic diagram.

Figure 8. - Exhaust gas analyses system.



(a) Condition 1: Inlet-air temperature 589 K (600° F); reference Mach number, 0.064; fuel-air ratio, 0.0158.

(b) Condition 2: Inlet-air temperature, 755 K (900° F); reference Mach number, 0.072. Open symbols denote fuel-air ratio of 0.0155; solid symbols denote fuel-air ratio of 0.0123.

(c) Condition 3: Inlet-air temperature, 838 K (1050° F); reference Mach number, 0.076; fuel-air ratio, 0.0155.

(d) Condition 4: Inlet-air temperature, 894 K (1150° F); reference Mach number, 0.078; fuel-air ratio, 0.0151.

Figure 9. - Effect of water injection on exhaust gas emissions.

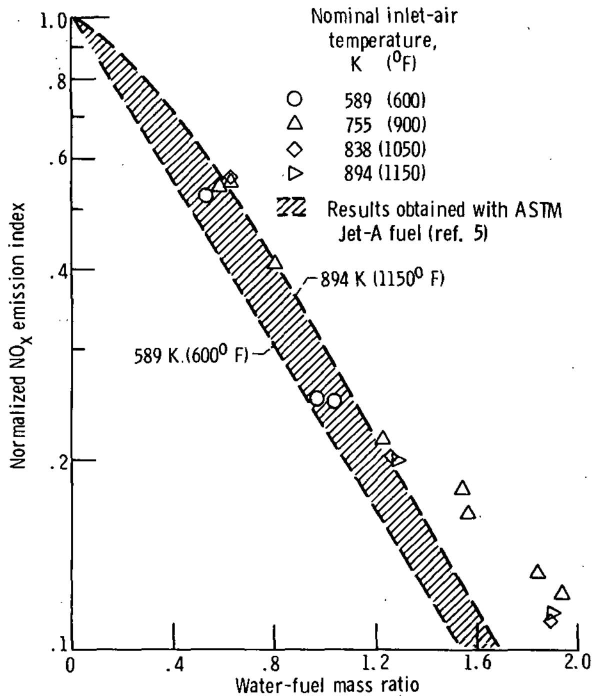


Figure 10. - Effect of water injection on normalized NO_x emission index; normalized to emission index at zero water injection.

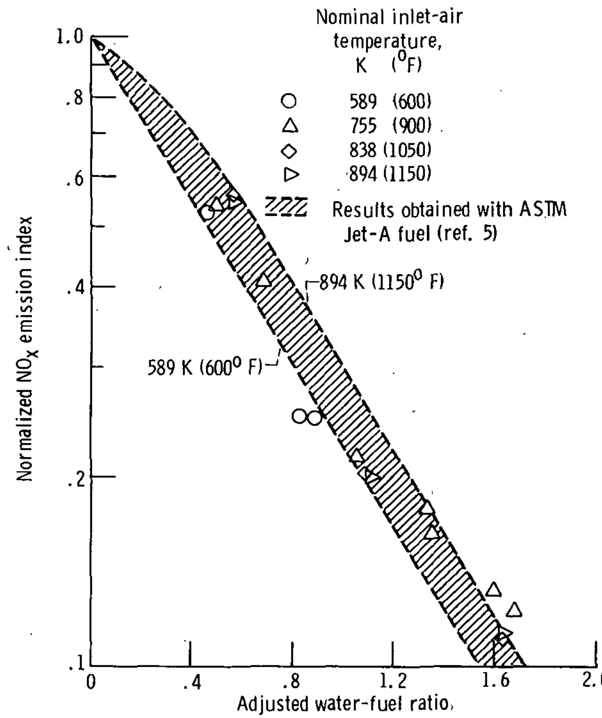


Figure 11. - Effect of water injection on normalized NO_x emission index. Water-fuel mass ratio adjusted to a Jet-A basis.

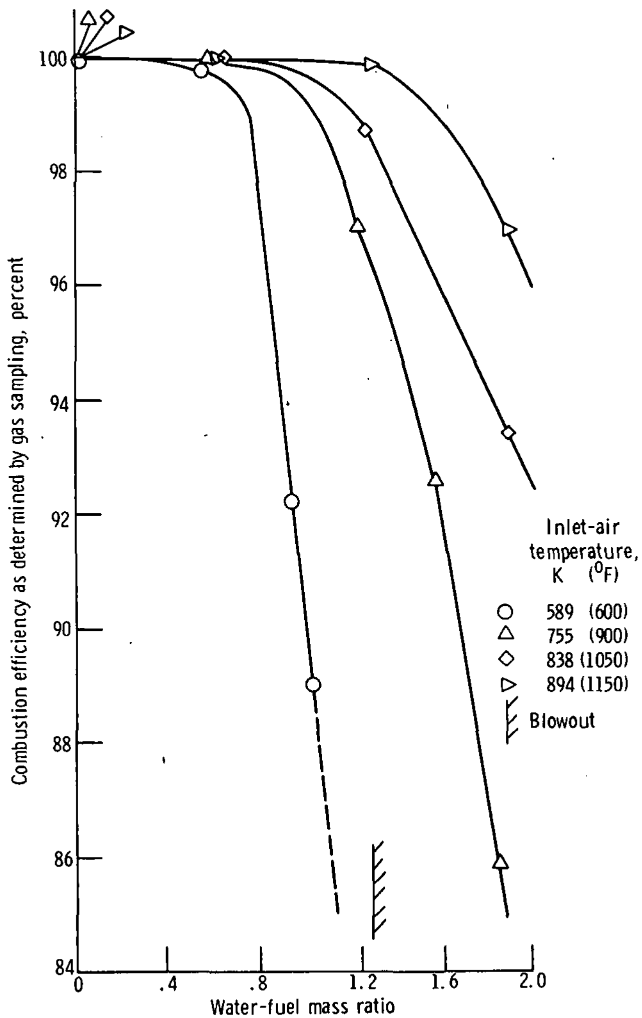


Figure 12. - Effect of water injection on combustion efficiency.

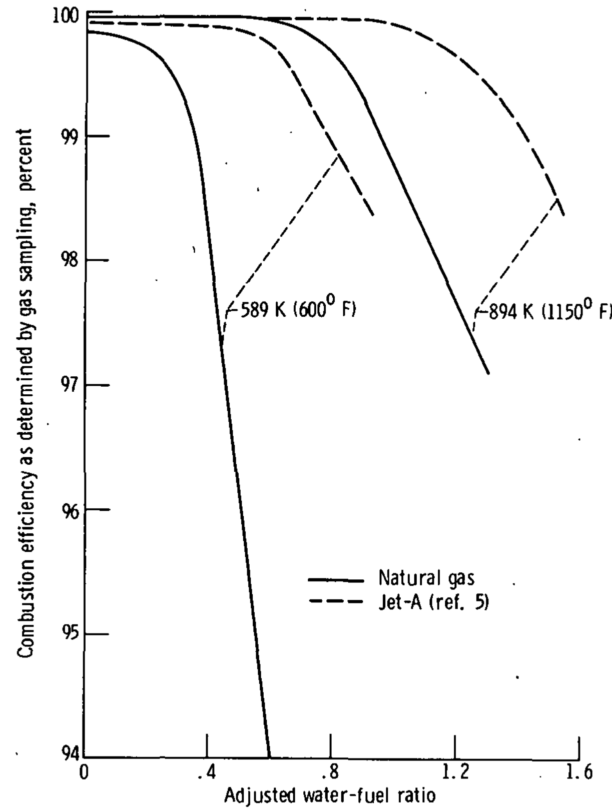
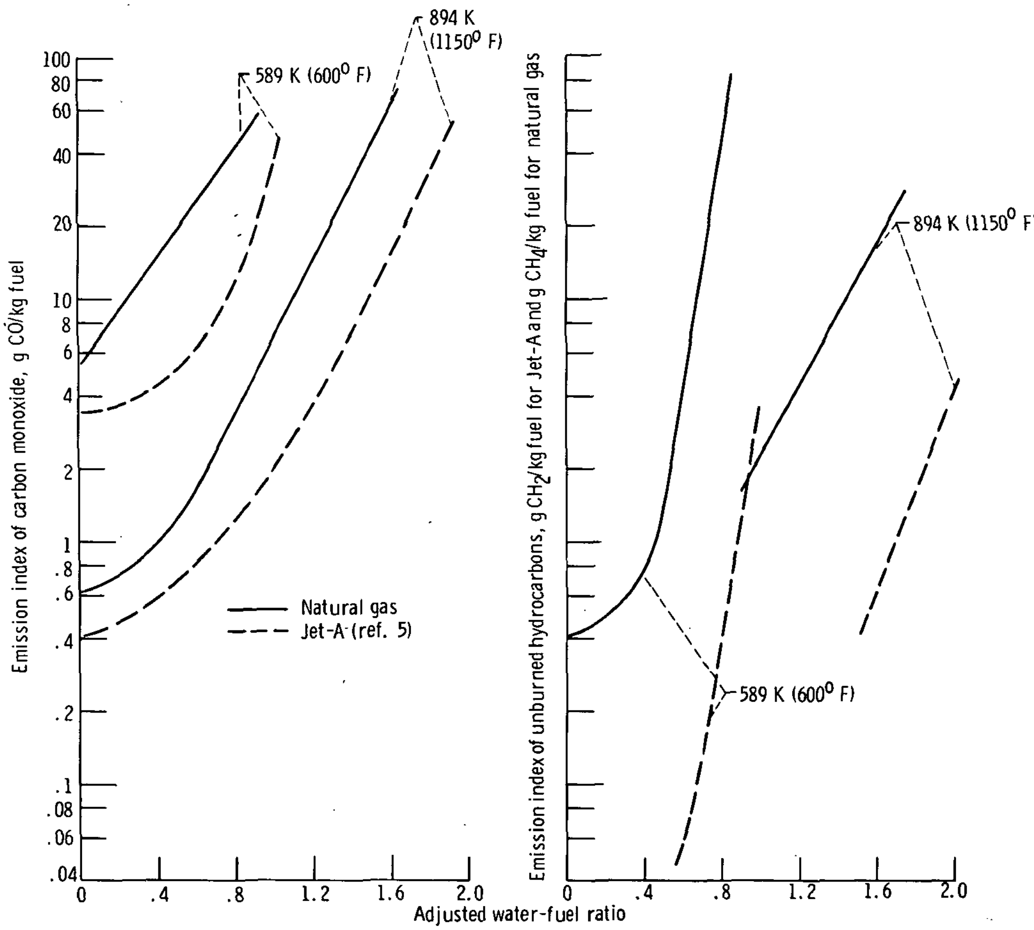


Figure 13. - Effect of water injection on combustion efficiency, comparing natural gas and Jet-A liquid fuel. Water fuel mass ratio adjusted to a Jet-A basis.



(a) Carbon monoxide.

(b) Unburned hydrocarbons.

Figure 14. - Comparison of unburned hydrocarbons and carbon monoxide emissions with water injection. Water-fuel mass ratio adjusted to a Jet-A basis.

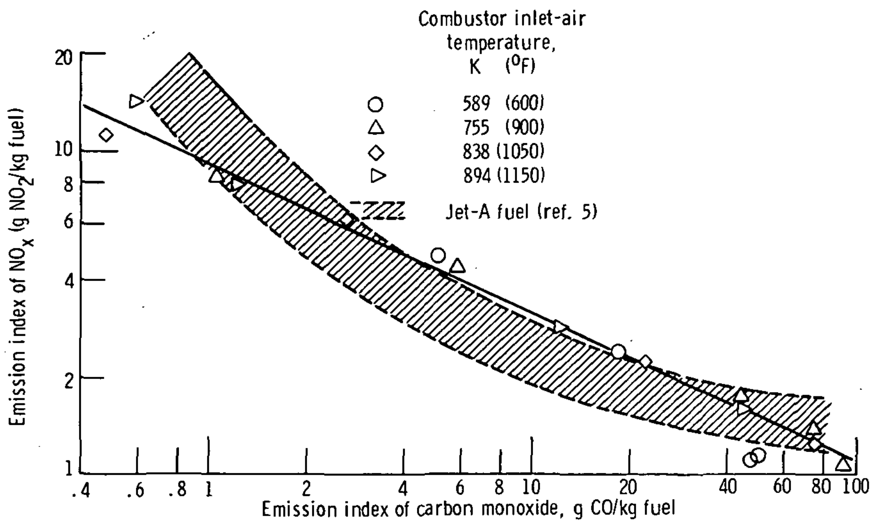


Figure 15. - Comparison of oxides of nitrogen and carbon monoxide emission indices with water injection for natural gas and Jet-A fuel.

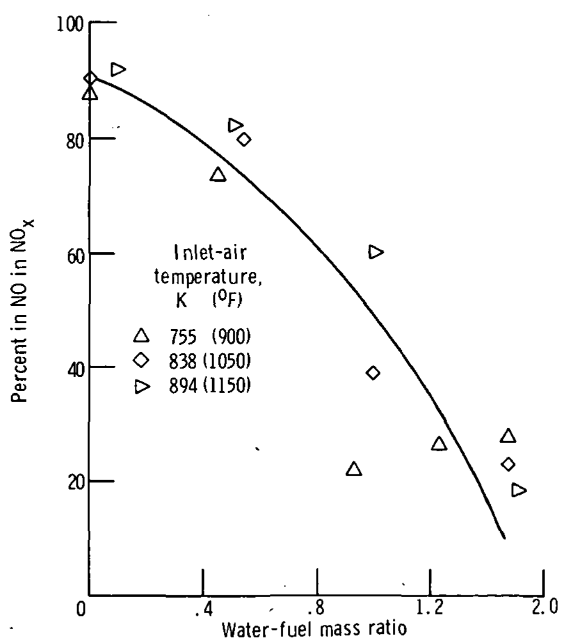


Figure 16. - Percent nitric oxide (NO) in oxides of nitrogen (NO_x) as affected by water-fuel mass ratio.

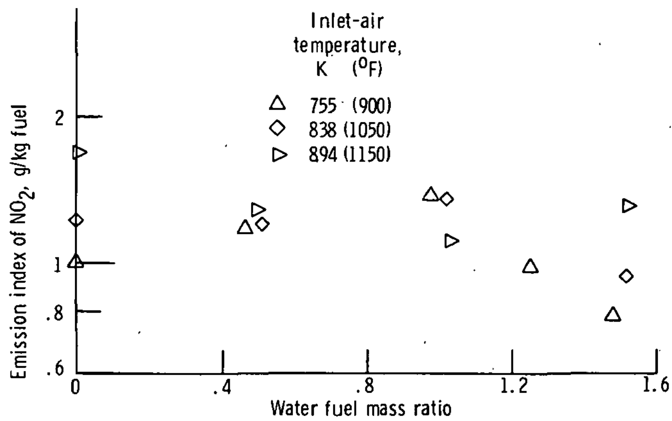


Figure 17. - Effect of water injection on nitrogen dioxide (NO_2) formation with natural-gas fuel.

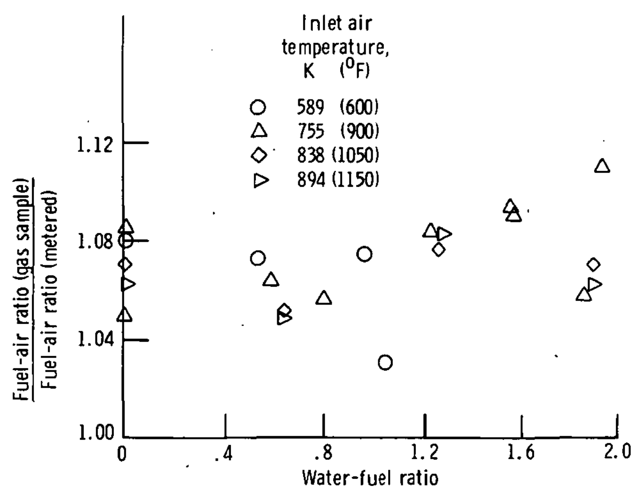


Figure 18. - Fuel-air-ratio ratio as affected by water-fuel ratio. Open symbols denote fuel-air ratio of 0.0155; solid symbols denote fuel-air ratio of 0.0123.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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